Coastal Ocean Observing System Modeling: Data Assimilation and Adaptive Sampling Design

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LONG-TERM GOALS

Accurate analyses of ocean currents, waves, temperature and salinity are required in order to forecast sediment and bio-optical properties in coastal waters that are critical to the performance of naval environmental sensors and operations. Analyses of these features can be significantly improved through the combination of observations and models by advanced data assimilation. With ONR support, the Regional Ocean Modeling System (ROMS) code has undergone extensive development and is being adopted by an expanding user community for ocean reanalysis and forecast applications. An important new enhancement in the modeling system is the formulation of tangent linear and adjoint codes and, built upon these, the capability for 4-dimensional variational data assimilation, sensitivity and stability analysis, and optimum generation of forecast ensembles to explore predictability limits. We will develop a coastal ocean modeling system that uses advanced data assimilation techniques with observations from new, rapidly deployable and relocatable coastal ocean observational assets to improve ocean forecasts in coastal regions that are of increasing interest to Navy operational requirements. Our system for regional ocean prediction will have the capability to use all available data from comprehensive coastal observational networks comprised of multiple CODAR installations, cabled observatories, autonomous gliders, and satellite imagery.

OBJECTIVES

To pursue the development of a prototype coastal ocean modeling, observation and prediction system for the Mid-Atlantic Bight. Specifically, we propose to:

(i) Demonstrate the capabilities of a coastal modeling system that utilizes data sets provided by relocatable observational assets such as CODAR and AUVs.
(ii) Integrate model and observations using 4-dimensional variational data assimilation.
(iii) Utilize the analysis tools underpinned by ROMS' tangent linear and adjoint codes to explore predictability, sensitivity, and adaptive sampling methodologies.
(iv) Evaluate model skill by comparison to a set of appropriately crafted model metrics.

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(v) Transition model results, capabilities and lessons to complementary observational studies in the Mid-Atlantic Bight (ONR's Shallow Water Acoustics 2006 (SW06) program).

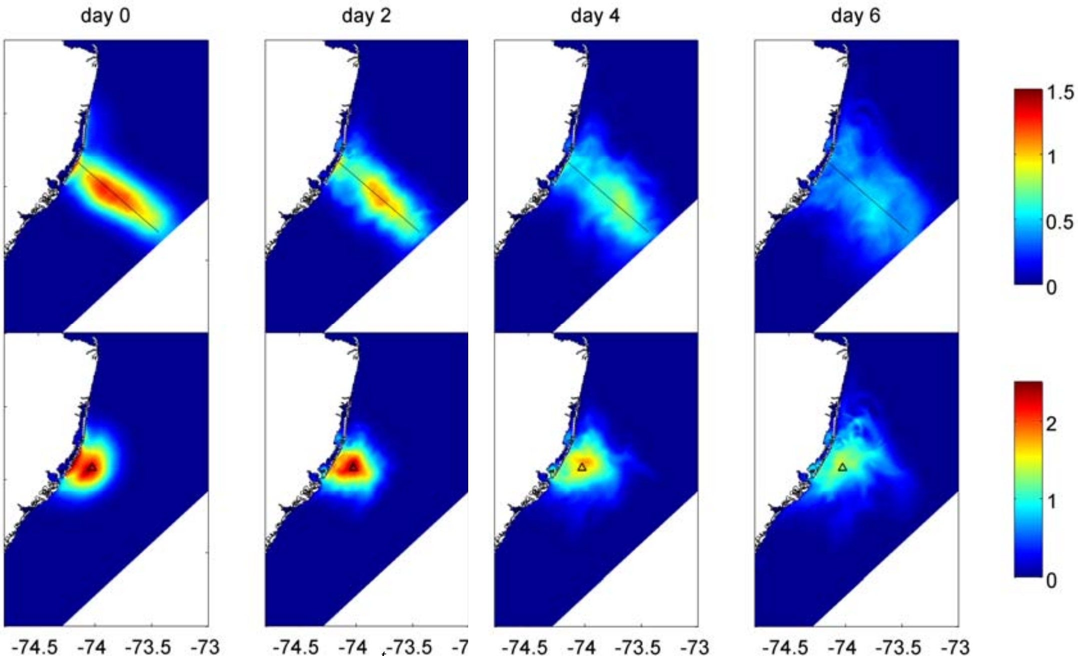
APPROACH

We use ROMS (the Regional Ocean Modeling System http://www.myroms.org), a split-explicit free surface primitive equations ocean model well suited to regional simulation applications from the basin to coastal and estuarine scales (Haidvogel et al. 2007). ROMS algorithms (Shchepetkin and McWilliams 2005) offer efficiency, stability and accuracy in coastal applications with both steep bathymetry and/or shallow water. Vertical turbulence closure options enable accurate simulation of boundary layer dynamics. Paramount among the ROMS features suited to a modern nowcast/forecast system are the adjoint and tangent linear codes and 4-dimensional variational (4DVar) data assimilation scheme. Variational assimilation seeks the model hindcast that minimizes a cost function measuring the model/observation differences over the analysis time period. The adjoint provides the cost function gradient with respect to a set of chosen model control variables such as the initial or boundary conditions, or surface forcing. A gradient-descent algorithm iteratively improves the control variables to achieve the best correspondence of model and observations. At the end of the analysis period, the model state represents the best nowcast. The model can then be integrated forward in a forecast mode using forecast surface and lateral boundary conditions. In Incremental Strong Constraint 4DVar (IS4DVAR), adjustment of the control variables (in our implementation the initial conditions for each forecast cycle) proceeds while assuming the model is error free over the analysis cycle, i.e. the model physics enter as a strong constraint because the forward model conservations equations are satisfied exactly.

WORK COMPLETED

A central Mid-Atlantic Bight ROMS model was configured for operational prediction of the ocean state during SW06, drawing on real-time in situ and satellite data sets from the Rutgers Coastal Ocean Observation Laboratory. The SW06 prototype system was a 5-km horizontal resolution, 30-level model with IS4DVAR assimilation of glider observations, shipboard CTDs and XBTs of opportunity on research vessel transit legs from Woods Hole, Scanfish profiles from RV Endeavor (Gawarkiewicz), underway thermosalinograph data from the first two RV Knorr legs, daily composite SST and gridded altimeter SSH anomalies. Initial conditions were the Linder and Gawarkiewicz New Jersey shelf climatology. Meteorological forcing was NCEP/NAM 12-km 3-hourly forecast data. Hudson River discharge data was from daily average USGS gauge observations. Tide boundary conditions were from the OTPS harmonic analysis. We assimilated data over 2-day intervals iterating the initial conditions to minimize the model-data misfit over each cycle. Each 2-day cycle begins with first guess initial conditions being the conclusion of the preceding interval.

This data assimilation methodology was further tested by reanalysis of observations from the April 2006 LaTTE field program tracing the discharge of the Hudson River plume. This more coastal domain was less prone to the influence of far field temperature/salinity bias and far field pressure gradient forcing of alongshelf transport, and enabled the testing of IS4DVAR assimimilation of surface velocity data from CODAR. This success prompted reconfiguration of the SW06 regional model domain to span the region from Cape Cod to Cape Hatteras by nesting within a still larger MAB-Gulf of Maine model (R. He, 2007, unpublished manuscript, http://omglnx1.meas.ncsu.edu/MABGOM). In conjunction with the IS4DVAR LaTTE reanalysis, evaluation of the relative information content of a single glider transect in comparison to continuous cabled observatory time series using a representer based approach.



$$J = \frac{1}{L(t_2 - t_1)} \int_{t_1}^{t_2} \int_{L} \left[(T - \overline{T})^2 + (S - \overline{S})^2 \right] dL\, dt$$

Figure 1: Representer functions for temperature and salinity anomaly variance. Comparison is for the observability of the ocean over a day 0-3 analysis interval and subsequent days 3-6 forecast window for (top row) a single glider traversing the indicted line and (bottom row) a continuous profiling CTD at the location marked by the triangle.

RESULTS

Climatology was a poor estimator of the initial state in 2006 given extreme precipitation in the Hudson River watershed during mid-July. While operational model assimilation quickly adjusted the salinity in the central SW06 region in response to low salinity observations by the gliders, in the absence of other data in the far field the adjustment was local. As the simulation proceeded, the salinity-corrected region advanced slowly northward and eastward consistent with the adjoint model propagating the model-data misfit information upstream. However, the barotropic transport of the shelf/slope front was not well constrained by the assimilation of predominantly temperature and salinity data, arguing in favor of the value of complementary observing systems (CODAR, ship ADCP, moored current meters) to constrain ocean velocities. The introduction of a low salinity core in the region of intensive observations generated a weak, unrealistic, anti-cyclonic circulation. As anticipated, this bias is reduced by adopting initial conditions that better reflect the shelf-wide anomalously low salinity (with respect to climatology) by nesting with the MAB-GOM model. The LaTTE Hudson River plume regime is understood well from related work (Choi and Wilkin 2007) to be a locally-forced advectively dominated regime with short time scales due to the responsive of the system to winds. We therefore choose this regime to evaluate a representer-based observing system design methodology because we could anticipate the analysis would show the advective pathways and time-scales associated with the plume behavior. Figure 1 shows an ensemble of all 3-day analysis (and subsequent forecast) intervals during 60 days of 2005 summer meteorological and river forcing. The results show that a 3-day assimilation interval for the IS4DVAR smoother is a reasonable interval because the initial conditions are correlated with the ocean state throughout the time period. The observations also influence the ocean state 3 days later, confirming the basis of LaTTE IS4DVAR results that useful skill is added to the re-analysis for periods extending to a 3-day forecast. Individual realizations (not shown) of the representers emphasize the 'observability' and 'forecast sensitivity' of each event and could be applied to inform the tasking of individual glider missions.

IMPACT/APPLICATIONS

Upon completion, the added assimilation of all SW06 field data (CODAR; in situ data from mooring and ships) will enable a re-analysis of the submesoscale ocean state during SW06, for subsequent analysis of the impact of resolved mesoscales on regional acoustic propagation and the internal waveguide. Choices made in implementing the IS4DVAR algorithm for this region (length scales, model and data error estimates, assimilation cycle length) have been contrasted for the SW06 (outer shelf) and LaTTE (inner shelf) regimes, will be explored further to seek more appropriate definitions of the background error covariance statistics that controls the unobserved null space.

RELATED PROJECTS

This project has strong synergies with ONR's NLIWI and AWACS DRIs that are companion to the SW06 program, and the Mid-Atlantic Bight shelf-wide MURI Experimental System for Predicting Shelf and Slope Optics (ESPreSSO). For the MURI we will introduce new componenets to ROMS is enable the inclusion of ocean bio-optics data in the assimilation procedure.

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